Laser $^{40}Ar/^{39}Ar$ dating of single detrital muscovite grains from early foreland-basin sedimentary deposits in India: Implications for early Himalayan evolution

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ABSTRACT

In India, the Dagshai and overlying Kasauli Formations represent the oldest exposed continental foredeep sediments eroded from the Himalayan orogen. $^{40}Ar/^{39}Ar$ dating of individual detrital white micas from these sedimentary units has provided maximum depositional ages of <28 Ma for the Dagshai Formation at one locality and <25 Ma at a second locality, whereas deposition of the Kasauli Formation occurred after 28 Ma at two localities and after 22 Ma at a third locality. This timing suggests that, in India, the start of substantial exhumation and erosion from the rising Himalayan orogen was delayed until 28 Ma.

INTRODUCTION

The important role played by erosion in the thermotectonic evolution of orogenic belts has been recognized from the time of early studies (e.g., England and Richardson, 1977; Johnson, 1981) through to the two-dimensional theoretical modeling undertaken by Ruppel and Hodges (1994). In this paper we seek to add new data on the problem of when significant uplift and erosion started in the Himalaya by determining the maximum ages of the earliest Himalayan-derived clastic foredeep sedimentary formations in India.

GEOLOGIC BACKGROUND

The Himalaya formed as a result of the collision between India and Eurasia. Collision was most probably diachronous west to east and began during the latest Paleocene–middle Eocene (e.g., Searle et al., 1988; Garzanti et al., 1996). The mountain range consists of southward-verging thrusts; the Main Central thrust and the Main Boundary thrust are two of the most important (Fig. 1). The Main Central thrust separates Indian plate basement rocks of medium to high metamorphic grade (the High Himalaya) from Indian plate rocks of a lower metamorphic grade (the Lesser Himalaya) below. Farther south, the Main Boundary thrust separates the Lesser Himalaya from the Sub-Himalayan foredeep, which contains Tertiary, Himalayan-derived sedimentary rocks. The Dagshai and overlying Kasauli Formation sedimentary rocks are the oldest clastic deposits in the Indian Himalayan foredeep (Bhatia, 1982). They crop out for more than 300 km along the mountain chain and provide valuable information on early Himalayan events and unroofing history.

The Dagshai Formation consists of red sandstones, siltstones, mudstones, and caliche. The lowest part of the succession is mudstone dominated; the sandstone:mudstone ratio increases upsection. The succession is interpreted as having been deposited under semiarid conditions in a distal alluvial fan, sheet flood, and fluvial system. The transition to the overlying Kasauli Formation is gradual and conformable. Gray sandstones dominate the Kasauli Formation. These rocks are interpreted as having been deposited under humid conditions in alluvial-fan and fluvial environments (Najman et al., 1993; Najman, 1995). The foredeep sedimentary units overlie the Paleocene–middle Eocene marine Subathu Formation and are, in turn, overlain by the sandstones and mudstones of the Lower, Middle, and Upper Siwalik subgroups.

The Dagshai Formation rocks are the first exposed products of erosion of the orogen. The sandy part of this sequence and the overlying Kasauli Formation mark the first major clastic input to the basin, interpreted as the start of significant exhumation and inferred uplift of the Himalaya.

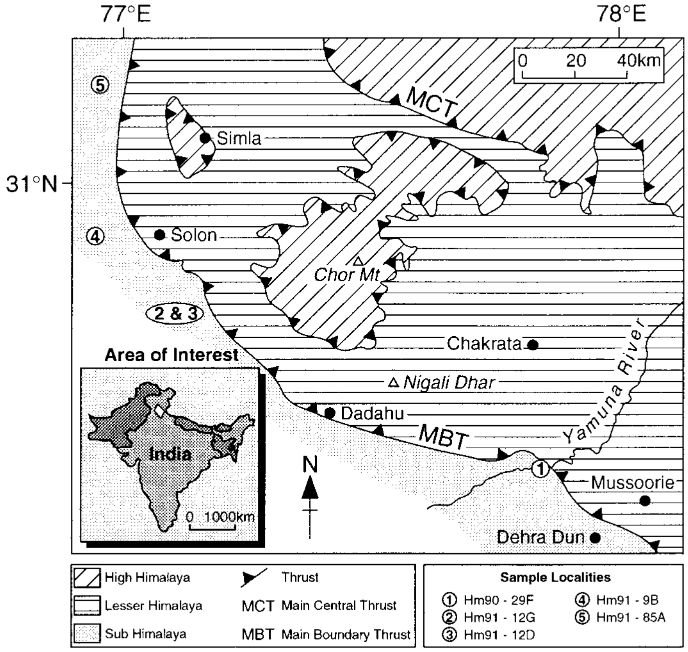

Figure 1. Simplified geologic map of study area, showing sample localities. Inset shows location of field area in relation to surrounding region.

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Data Repository item 9729 contains additional material related to this article.

Limited age information for the lower Tertiary sedimentary rocks can be gained from stratigraphy, paleontology, and paleomagnetic studies. The conformably underlying Subathu Formation is paleontologically dated as extending from the Paleocene to the early part of the middle Eocene (Mathur, 1978). A paleomagnetic study (Najman et al., 1994) produced a depositional age of 35.5 ± 6.7 Ma for the Dagshai Formation; this age is an average for the succession, and therefore the age of the base and top of the sequence should be, respectively, older and younger than this average. The age determined paleomagnetically appears to be at variance with the new Ar-Ar detrital mica age data reported in this paper. Inherent inaccuracies associated with the paleomagnetic technique, including uncertainties in the Indian apparent-polar-wander path, and tectonic shortening estimates of the Sub-Himalaya, could be responsible for the apparent age discrepancy, which nevertheless approaches being within error for one of the two Dagshai Formation samples. The paleomagnetic dating was a first step toward interpreting the Dagshai Formation as younger than the Subathu Formation, an important result as the Dagshai was previously considered by some workers as being of equivalent age to the Subathu Formation (Raiverman and Raman, 1971). However, the Ar-Ar dating in this paper represents a significant advance in accuracy.

An early Miocene age is generally assumed for the Kasauli Formation, on the basis of the occurrence of early-middle Miocene plant remains (Fiestmantel, 1882) and Aquitanian mammal remains (Pilgrim, 1910; Bossart and Ottiger, 1989) in the broadly correlative Murree Formation of Pakistan (e.g., Gansser, 1964). The age of the overlying Lower Siwalik subgroup provides a further constraint but, in India, is only poorly constrained at an approximate average of 15 Ma (Lyon-Caen and Molnar, 1985). In Pakistan, the base of the Lower Siwalik sensu stricto (i.e., the base of the Chinji Formation) has been dated as 14.3 Ma (Johnson et al., 1985). However, the Kamlial Formation, dated as 18.3–14.3 Ma, underlies the Chinji Formation, and confusion exists as to whether the Kamlial Formation should be assigned to the Lower Siwalik subgroup (e.g., Pilgrim, 1910; Johnson et al., 1985) or to the underlying Murree Formation (e.g., Cotter, 1933), which is a correlative of the Dagshai and Kasauli Formations in India.

This study has enabled us to constrain more accurately the depositional ages of the lower Tertiary foredeep sedimentary units, on the basis of the fact that a sediment will be younger than or equal to the age of the youngest unaltered detrital mica it contains.

^{40}Ar-^{39}Ar DATING OF DETRITAL WHITE MICAS

Methodology

Single crystals of muscovite were separated from two Dagshai and three Kasauli Formation sandstones, from localities shown in Figure 1. Between 6 and 13 handpicked muscovites from each sample were analyzed by using single-step total fusion. Four further muscovites were subjected to incremental step heating of as many as five steps. ^{40}Ar/^{39}Ar analyses were measured by using the argon laser probe at the Vrije Universiteit, Amsterdam, as described by Wijbrans et al. (1995), except that the electron multiplier was operated at a gain of 40 000, instead of 10 000. In addition, muscovites from the same samples were analyzed by using the electron microprobe as a test of alteration of the samples. Illite crystallinity was also used to determine if postdepositional temperatures were sufficient to cause resetting.

Results

^{40}Ar/^{39}Ar Muscovite Ages. Table 1 summarizes the results of the ^{40}Ar/^{39}Ar dating.[1] Most samples show a considerable spread of muscovite ages, as expected for sediment derived from various sources. The Kasauli Formation possesses the youngest muscovites, and the younger muscovite:older muscovite ratio is generally higher compared to the Dagshai Formation. The Dagshai Formation has the oldest muscovites. A significant proportion of the dates falls between 35 and <22 Ma.

TABLE 1. ^{40}Ar/^{39}Ar AGES, WHITE MICA, DAGSHAI AND KASAULI FORMATIONS

Dagshai 90-29F	Dagshai 91-12G	Kasauli 91-12D	Kasauli 91-9B	Kasauli 91-85A
		Single grain ages (Ma)		
24.7 ± 0.7	100.7 ± 0.3	35.1 ± 0.2	23.2 ± 0.1	69.9 ± 0.5
24.6 ± 0.4	26.6 ± 0.4	63.1 ± 0.2	23.9 ± 0.6	27.6 ± 0.3
24.6 ± 0.9	28.3 ± 0.4	44.2 ± 0.2	25.4 ± 0.4	33.7 ± 0.6
24.7 ± 0.6	135.2 ± 0.3	28.7 ± 0.2	81.0 ± 0.4	27.7 ± 0.2
330.2 ± 1.0	346.6 ± 1.4	28.6 ± 0.3	22.0 ± 0.4	29.7 ± 0.5
22.4 ± 1.1	72.1 ± 0.3	77.8 ± 0.3	24.3 ± 0.3	162.0 ± 1.2
25.2 ± 0.6	49.8 ± 0.5	27.2 ± 0.5	25.3 ± 0.1	
	27.0 ± 1.0	31.7 ± 0.7	23.9 ± 0.4	
	43.5 ± 0.3	44.8 ± 0.3	54.7 ± 0.3	
	85.6 ± 0.8	27.7 ± 0.3	22.2 ± 0.2	
	25.3 ± 0.6			
	32.0 ± 1.7			
	114.8 ± 1.5			
	28.2 ± 1.1			
	27.5 ± 0.4			
		Modes (Ma)		
24.7	28.0	27.6	22.1	27.7
		28.7	23.2	
		44.2	24.2	
			25.3	

Formation and sample numbers as column headings.

Note: Single-crystal (total fusion, total gas ages from step-heating experiments) ages reported to 85G003 TCR sanidine @ 27.92 Ma; errors reported as 1 standard deviation of analytical precision. See footnote 1 in text.

The frequency profiles in Figure 2 sum the Gaussian error distribution curves for the individual grains in each sample using the calculated ages and standard deviations as reported in Table 1. Samples with small error bars show up as high, narrow peaks, and those with large error bars show up as low, wide peaks. This process allows us to identify modes representing the most probable mica ages in each sample. In this study, only modes defined by two or more analyses are considered, because it is inadvisable to place too much significance on a single data point. Modal values for all samples are given in Table 1.

Muscovite Alteration. Incremental step heating, electron-microprobe analyses, thin-section examination, and illite crystallinity were used to assess the degree of alteration of the micas (i.e., the potential for either postdepositional resetting or alteration by weathering in the source area).

Incremental Heating. Incremental heating during ^{40}Ar/^{39}Ar dating was carried out on four muscovites from three samples (Fig. 3). All produced flat spectra, indicating no detectable signs of alteration in the ^{40}Ar/^{39}Ar age spectra.

Electron-Microprobe Analyses. Alkali loss in muscovites is a good indicator of alteration. Electron-microprobe traverses were run on three to five muscovites from each sample (representative results in Fig. 4). In most cases, total alkali contents are typical of unaltered micas, and any alteration is often confined to the edge of the mica grain, where clear gradients can be seen.

Thin-Section Examination. Many of the white micas appeared fresh and relatively unaltered in thin section, although some grains showed signs of alteration, mainly at the rim or along cleavages. Micas in Kasauli Formation sample Hm91-85A appeared to be more altered compared to grains from the other samples.

Illite Crystallinity. Illite crystallinity provides a measure of the degree of metamorphism that a rock has been subjected to. Measurements were made on the <2 μm fraction of Dagshai and Kasauli Formation mudstones from a number of localities. A small size fraction was used in order to measure the diagenetic component of the rock rather than a detrital signature. All samples fell into the diagenetic to lower anchizone zones, implying diagenetic tem-

[1]GSA Data Repository item 9729, Analyses of Himalayan white mica grains, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

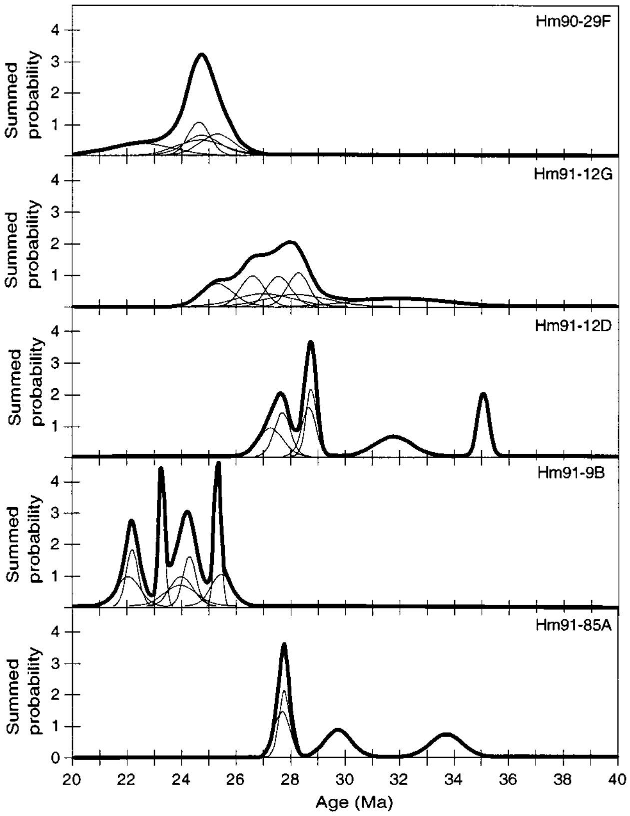

Figure 2. Frequency profiles of Gaussian error distribution curves for micas younger than 40 Ma from each locality. Each curve corresponds to individual mica. Curve shown in bold is sum of underlying curves.

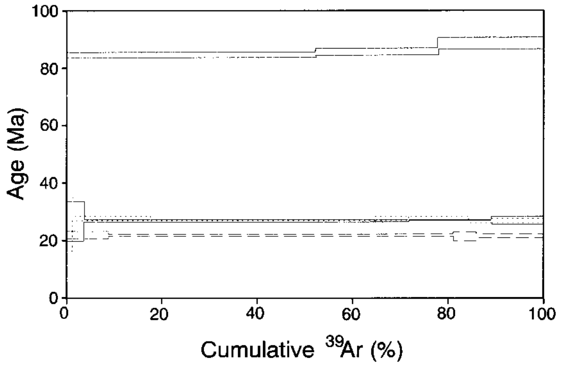

Figure 3. Incremental-heating age spectra of single muscovite grains from Dagshai Formation (two grains, sample Hm91-12G, solid line) and Kasauli Formation (Hm91-9B, dashed line, and Hm91-12D, dotted line). Height of individual steps is ±1 standard deviation of apparent age.

peratures of ~<200 °C (Kubler, 1967; Blenkinsop, 1988), insufficient to cause postdepositional resetting of the micas.

Dating of the Sediments. ^{40}Ar/^{39}Ar dating of individual detrital white micas permits us to place a maximum depositional age on the sedimentary rocks; they are younger than the detrital mica age that records the time of mica cooling through ~350 °C in the source area, the difference being the time required to denude ~10 km of overburden. We can therefore (1) date the Dagshai Formation from two localities as <25 Ma and <28 Ma and (2) date the Kasauli Formation as <28 Ma at two localities and <22 Ma at a third locality.

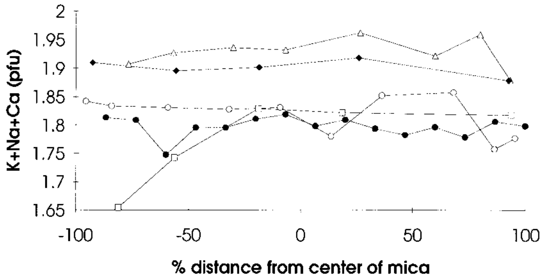

Figure 4. Traverses across selected micas showing variation in alkalis within grain as indication of levels of alteration. K + Na + Ca is plotted in stoichiometric formula units (pfu = per formula unit). Samples: triangle—Hm91-12D, diamond—Hm90-29F, white circle—Hm91-85A, square—Hm91-12G, black circle—Hm91-9B.

DISCUSSION

This work enables us to place a maximum age on the deposits that record the start of substantial erosion and exhumation of the Himalaya. Although the fine-grained, lowest part of the Dagshai Formation, which is mica free and therefore undatable by this method, will be older than the ages calculated from the overlying sandier parts of the Dagshai Formation, this fact is unlikely to significantly affect our interpretation. The lowest part of the Dagshai Formation is insignificant in terms of thickness; therefore, if these lowest Dagshai rocks were notably older than the ages given for the overlying sandstones, sedimentation would have been extremely slow during this initial period, a situation not signifying substantial earlier exhumation of the orogen. Furthermore, the lowest Dagshai Formation is mud dominated; the lack of a notable clastic component suggests that substantial erosion and exhumation of the orogen was not occurring during this time. Thus, the start of significant Himalayan erosion, indicated by the first substantial input of clastic material to the basin, is reflected in the sandier material of the Dagshai Formation above the lowest, thin, mudstone-dominated strata, and the overlying Kasauli Formation, both of which we have now dated by using detrital micas. Hence, the start of significant Himalayan erosion and exhumation occurred after 28 Ma. A potential connection between deposition of the early foredeep sediments and movement along the Main Central thrust, active by 24–21 Ma (Hubbard and Harrison, 1989; Harrison et al., 1995), should also be noted.

The inference from the above is that there is no clear evidence of a substantial clastic sedimentary signal from the evolving orogen before 28 Ma. Why is this so, as crustal thickening and metamorphism are thought to have occurred by this time (Frank et al., 1977; P. Zeitler in Hodges and Silverberg, 1988; Inger and Harris, 1992; Searle, 1996, and references therein; Vannay and Hodges, 1996)? A number of possibilities exist: (1) Crustal thickening and metamorphism had not occurred in the source area by this time. (2) Crustal thickening, metamorphism, exhumation, and erosion had occurred in the source area by this time, but the deposits are either not preserved or not exposed in the foredeep. (3) Crustal thickening and metamorphism had occurred in the source area, but exhumation had not.

Option 1 is unlikely because available evidence would seem to refute any suggestion that early "Eo-Himalayan" metamorphism and crustal thickening, dated as early Eocene–early Oligocene, did not occur (P. Zeitler in Hodges and Silverberg, 1988; Inger and Harris, 1992; Vannay and Hodges, 1996).

Option 2 would require that the early sediment bypassed the foredeep and was deposited in marine fans or that it was buried beneath more northerly thrust sheets. Drilling by the Ocean Drilling Program on the Bengal Fan (Leg 116) did not penetrate the base of the fan, but sedimentological and seismic criteria suggest that the base was approached and that the onset of fan sedimentation dates from the early Miocene (Cochran, 1990). However, terrigenous material of late Eocene and early Oligocene age in the Arabian Sea was presumed by Kidd and Davies (1978) to have been derived from the Himalaya. In addition, Lyon-Caen and Molnar (1985) have calculated that a small quantity of foredeep sedimentary deposits may have been thrust beneath the Himalaya, although they suggest that most sediment was probably accreted to form the foothills of the range. Very small volumes of foredeep sediments are also found beneath more northerly thrust sheets (Najman et al., 1993). Although these deposits are largely the Paleocene–middle Eocene nonclastic marine Subathu Formation lithologies and lowest Dagshai Formation mudstone, it could be that an overlying clastic succession was detached by thrusting. Therefore option 2 cannot be discounted, although along strike in Pakistan, late Paleocene–middle Eocene foredeep rocks are exposed at the same structural position beneath the Main Boundary thrust as the Dagshai and Kasauli formations in India (Bossart and Ottiger, 1989). This fact suggests that remoteness from the early evolving mountain front did not preclude a sedimentary response and that the exposed foredeep sediments do record the complete early evolution of the orogen.

Option 3 requires delayed exhumation in response to crustal thickening. Formation of a cold dense root, either by orogenic thickening affecting the whole lithosphere (Fleitout and Froidevaux, 1982; Platt and England, 1994) or by eclogitization of the lower crust (Richardson and England, 1979; Dewey et al., 1993), inhibits uplift. Uplift finally occurs owing to either convective removal of part of the mantle lithosphere or warming of the cold root. The former mechanism results in sudden rapid uplift, and the latter mechanism produces gradual uplift. Because the Indian Himalayan foredeep sedimentary record suggests a gradual increase in sedimentation through time, delayed uplift followed by gradual warming of the cold dense root would be the more likely scenario. If this is the case, it has far reaching implications for the modeling of tectonothermal processes in the continental lithosphere and mechanisms of orogenic development.

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